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(71) Applicant: IDC, LLC [US/US]; 2415 Third Street, San Francisco, California 94107 (US).

(72) Inventors: KOTHARI, Manish; 811 Mediterranean Lane, Redwood City, California 94065 (US). CUMMINGS, William, J.; 105 Woolsey Street, San Francisco, California 94134 (US).

(74) Agent: MALLON, Joseph, J.; KNOBBE, MARTENS, OLSON & BEAR, LLP, 2040 Main Street, 14th Floor, Irvine, California 92614 (US).

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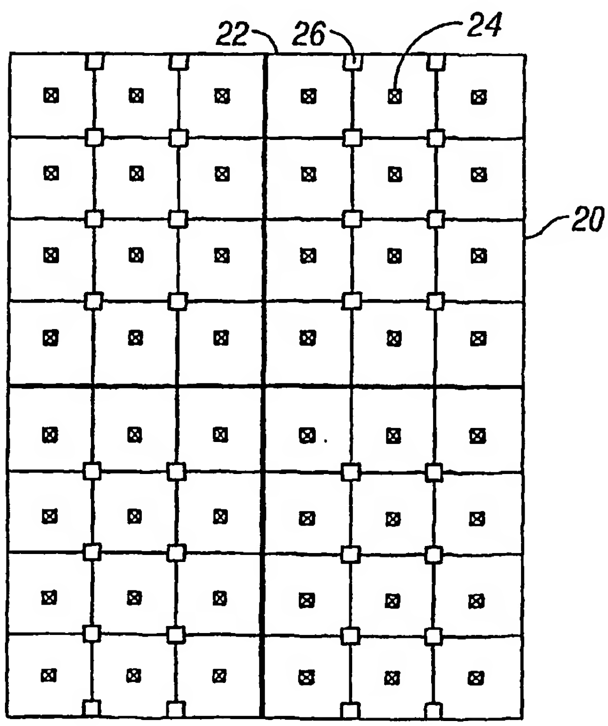
(54) Title: ALTERING TEMPORAL RESPONSE OF MICRO ELECTROMECHANICAL ELEMENTS



(57) Abstract: An array of movable elements is arranged on a substrate. Each element has a cavity and a movable member to move through the cavity. The pressure resistance of the elements varies, allowing actuation signals to be manipulated to activate elements with different pressure resistance at different levels of the actuation signal.

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ALTERING TEMPORAL RESPONSE OF MICRO ELECTROMECHANICAL ELEMENTS

Background

Microelectromechanical (MEMS) systems are generally made up of individual moving elements manufactured on a micrometer scale. Such elements as switches tunable, capacitors, mirrors for display and printing applications, etc., serve as MEMS examples. For purposes of this discussion, a MEMS device has at least one movable element, a cavity into or out of which the element moves, and some sort of actuation signal that causes the element to move.

In some applications, the actuation timing of the element, where the actuation is the movement of the element from one position to the next position, is a key portion of the operation of the device. In MEMS switches, for example, the switch elements may be cascaded and the response time of a first switch may determine the response time of the next switch, etc. In MEMS displays, the movement of the elements generally modulate light, and the timing of the modulation determines the image content seen by a viewer.

Having finer control of these elements by their response times may afford better operation, such as a higher image quality. Control of display elements by their response times, for example, may provide a higher bit depth for display applications.

Brief Description of the Drawings

The invention may be best understood by reading the disclosure with reference to the drawings, wherein:

Figure 1 shows an embodiment of a microelectromechanical element.

Figure 2a and 2b shows graphs of operational times related to pressure.

Figure 3 shows an embodiment of an array of display elements.

Figures 4a and 4b show cross-sections of alternative embodiments of a display element.

Figure 5 shows an actuation/release response curve for an embodiment of a display element.

Figure 6 shows an alternative embodiment of an array of display elements.

Figure 7 shows an actuation/release response curve for an alternative embodiment of a display element.

Figure 8 shows an embodiment of a picture element comprised of several display elements having differing levels of pressure resistance.

Figure 9 shows an alternative embodiment of a picture element comprised of several display elements having different levels of pressure resistance.

Figure 10 shows an alternative embodiment of a picture element having rails for support.

Detailed Description of the Embodiments

Figure 1 shows a diagram of a generalized structure for a micromechanical element 10. This movable element 10 has a movable member 14 adjacent a cavity 18. Opposite the movable member 14 lies an actuator 16 of some sort, such as an address transistor or other component that allows actuation of the movable element towards the substrate 12 into the cavity 18. Typically, the element will be suspended over the substrate, but may also be oriented horizontally across the cavity, or the actuator may be the suspended portion of the movable element 10. Similarly, the movement through the cavity may be the motion of the member 14 into the cavity 18, as would occur if a member went from a position like member 14a to a position parallel to the position of member 14b. Alternatively, the movement may be in the opposite direction, starting at position 14b and ending at a position parallel to the position of member 14a.

When the member moves towards the substrate, gas trapped in the cavity 18 must escape. Depending upon the provisions made for such escape, the response time of the element may be affected. The response, or actuation, time is that period of time it takes for the movable member to reach its actuated position. If there is very little space allowed for the gas to escape, the mechanical resistance of the gas may act as a damping agent on the motion of the movable member of the element. This damping due to mechanical resistance will be referred to here as pressure resistance. The pressure resistance can be exploited to allow finer control of the response of the elements.

Air or other gases under pressure may act as if they were fluids, and the resistance caused by the gas is similar to that of viscous fluid damping. When the gas resides in a gap that is very small, it no longer acts as a fluid, but resists movement by the pressure of the gas itself. The pressure would be calculated in the small gap case with the formula of Pressure*Volume = constant. In the case of movable elements, the pressure resistance of the gas between the movable element and the substrate or other fixed structure may be viscous fluid damping initially, and as the gap closes become pressure as characterized above.

This pressure resistance may be manipulated by varying the pressure resistance across the elements, where different elements have different pressure resistances and therefore have different response times. A different approach, where the response time is altered for movable elements by gas holes is discussed in US Patent Application Serial No. 09/966,843, "Interferometric Modulation of Radiation," filed September 28,2001. In that approach, the desire was to speed up the response time, and all of the elements had the same pressure resistance as they all had the same pattern of holes. As the movable elements deflect, they all have uniform pressure resistance.

A graph of response time versus pressure is shown in Figure 2a. As can be seen from the 3 different plots, gas pressure is the dominant factor in the response of the device. Figure 2b shows the response times of two different elements. The top curve is the response time for an element

tuned to have a slower response. The bottom curve is the response time for an element tuned to have a faster response. This variation of pressure resistance between the devices can be exploited.

The variation of pressure resistance can be applied to different movable elements. These include switches, different types of display elements, tunable capacitors, etc. With regard to display elements, providing extra spaces for the gas to escape may speed the response time. In display applications, MEMS elements are typically arranged in an x-y grid on a substrate. Depending upon the size of the elements, they may be further grouped into subarrays, where each subarray forms a picture element, or pixel, of the resulting image seen by a viewer. A portion of such an array is shown in Figure 3.

In Figure 3, a portion of an array of movable elements is shown. The movable elements are grouped into subarrays corresponding to pixels, such as subarray 20. Each element in the array comprises a surface having a hole in the center to allow the gas to escape when the movable member of the element is actuated and moves. While this particular structure is based upon an interferometric modulator, these holes could be used for many different types of structures. To vary the pressure resistance of the element, the size of the holes would be varied, providing elements with different response times.

Interferometric modulators, such as the iMoD^{TM}, rely upon interference effects operating on light inside the cavity to modulate the light in accordance with image data. A cross-sectional view of such a modulator is shown in Figure 4a. In this embodiment, the viewing surface would be at the 'bottom' of the picture. The modulator array is formed on a transparent substrate 30. An optical stack 36 forms a first optically active surface that may be affected by the second optically active surface, the mechanical or mirror layer 33. A dielectric layer 38 typically protects the optical stack layer. The mechanical layer 32 is supported by posts such as 32, with the location of posts forming the individual elements of the array.

When the circuitry on the substrate, not shown, is activated in a particular region under the mechanical layer, such as that portion of layer 34 that is suspended over cavity 40, the mechanical layer deflects towards the optical stack 36. As it deflects, the mechanical layer causes the portion of the optical stack as seen by the viewer to appear black. Therefore, by addressing the mechanical layer with image data, an image would be seen by the viewer. This particular embodiment of an interferometric modulator may be referred to as a monolithic interferometric modulator here.

In an alternative embodiment of an interferometric modulator shown in Figure 4b, the mirror 44 that causes the pixel to appear black when deflected is separated from the support layer 42. This may be referred to as a separable modulator here. In either case, the trapping of gas that is resident inside the array packaging may be used to alter the response time of the movable elements. The general principles of such will be discussed with regard to the monolithic embodiment, with adaptations for the separable modulator being discussed later.

In one embodiment of the modulator, the layer 34 of Figure 4a may be seen by the viewer. However, the holes are so small that no objectionable artifacts would typically be created by forming holes in the center of the portions that actuate. In Figure 4b, the holes would be made in the mirror 44, in the supporting layer 42, or both. Holes made in the supporting layer 42 would not be seen by the viewer, as they would be shielded by the mirror 44. By adding the holes to the surface, the response time would be altered. The response time for this type of element is shown in Figure 5. As can be seen these elements have a response time of approximately 200 microseconds.

In contrast, a portion of an array of elements without the holes is shown in Figure 6. The pixel 50, comprised of several subpixels and referred to here as a macropixel, would have individual elements such as 52, without holes in their surfaces, and edge 51 is a free edge represented by a dashed line. The response time for this type of modulator is shown in Figure 7. As can be seen, the response time approaches 3 milliseconds. In the experiments conducted to gather this data, the two modulators were manufactured from the same wafer, so other factors, such as dielectric charging, that might affect the response time would be similar for both. The longer response time is only due to the trapping of the gas under the modulator elements.

This characteristic can be exploited to provide finer control of the movable elements. For example, in the monolithic modulator, such as that shown in Figure 8, the edge elements 70a-j may be manufactured to have a lower mechanical resistance than the elements in the middle of the pixel 72a and b. When an actuation signal is applied at a first level, such as the beginning portion of a ramp signal, the edge elements would move first, having less mechanical resistance to the attractive forces drawing the movable member towards the substrate. As the edge elements move, they cause gas to be trapped under the elements in the middle of the pixel, in this example 72a and 72b. One method of fabricating modulators having different mechanical stiffness can be found in US Patent No. 6,574,033, "Microelectromechanical System Device and Method for Fabricating Same," issued June 3, 2003.

The trapped gas provides another opportunity to control the response time of the final two elements of the pixel. As the actuating signal attains a second level, the middle elements would then move. In this manner, controlling the voltage allows a system designer to provide pulses of varying times or voltages to determine how many elements of a pixel move and affect the resulting pixel seen by the viewer.

Other variations on this approach without holes exist. For example, a first set of elements on a free edge of the pixel, such as 70a, 70d, 70f and 70h could be designed to deflect first. A second set of elements on a second free edge, such as 70c, 70e, 70g and 70j could then move after the first set, instead of simultaneously as discussed above. The mechanical resistance as discussed above could control the movement timing. It may be desirable to move the first edge and the second edge simultaneously in some applications, or separately in others.

An example of an approach that varies the mechanical resistance may include altering the post spacing of the modulator posts. The modulator of Figure 8 has wider gaps between the posts of the edge pixels 70a-70j, than those posts used for the elements in the middle. This can be seen more clearly by comparing element 52 of Figure 6 with element 70c of Figure 8. Other types of variation of mechanical resistance are also possible.

In an alternative embodiment, it is possible to form holes in the back surfaces of the movable elements, as is shown in Figure 9. The center elements 82a and 82b have center holes that allow any trapped air to escape. This may allow for another level of response time. The edge elements having a lower mechanical resistance to the actuation signal may respond first, then the middle element 82a with the hole, followed by the element 82b without the hole. Again, this allows control of the actuation signal to different levels to effect different numbers of elements used to form the resulting pixels.

In the above embodiments, then, there is provided an array of movable elements. Each element has a movable member and a cavity through which the member moves. The pressure resistance of the elements are varied such that at least one element has a different level of pressure resistance than the other elements in the subarray or pixel. The difference may be because of air forced under the element by the collapse of neighboring elements, or because of the presence or absence of holes patterned into a surface of the element.

Returning to Figure 4b, it is possible that these general principles may be applied to elements not having the advantage of the monolithic mirror or mechanical layer such as those discussed above. The movable element 44 may also be formed with holes in it, allowing trapped gas to escape. Alternatively, the support layer 42 may be manufactured to be larger than shown here, so as to move and cover the edges of the mirror when the mirror moves, thereby trapping gas under the mirror. In addition, channels could be manufactured to restrict. or release air between the mirrors.

In another alternative, the mirror 44 could be formed of two parts or two layers. The first layer would be larger and thinner than the second. The second layer would be deposited on the first, but have less surface area, forming a mirror having a center, rigid portion and a flexible outer portion. When the mirror moves, the flexible portion would collapse first and trap gas under the edges of the mirror.

In another embodiment, it is possible that the mirrors or movable elements be supported on all four sides, with the mirror resting on 'rails.' This is shown in Figure 10 where there are not any posts, each sub element and each macropixel being supported from the sides.. Any gas trapped under the macropixel 90 would be isolated from any gas trapped under macropixel 96. One embodiment would have the rail 98 between the two macropixels being manufactured so as to not allow any gas movement. In addition to the holes in the individual subpixels, it would then be possible to also control the response time by forming or choosing not to form holes in the rails

around the subpixels, such as between 92a and 92b. If holes are formed in the rails, the gas would be allowed to escape more quickly when under pressure from a moving element, and the response time would be altered.

In yet another embodiment, the substrate may be patterned with structures, such as bumps or grooves to facilitate gas movement. This additional aspect would be applicable to any of the previously mentioned embodiments. It is also possible that the movable element itself would have bumps on it to facilitate gas movement. The patterns of the bumps and grooves may vary across different elements of a macropixel, to provide the variable pressure resistance desired.

In addition to alternative types of elements being used, the two interferometric modulators merely serving as examples of devices to which this invention could be applied, it is possible that the gas-trapping characteristic can be exploited on the release part of the cycle rather than the actuation portion. This was discussed above with regard to Figure 1. However, given the amount of space on the backside of the mirror and the packaging complexities involved, trapping gas on the actuation cycle is probably more practical. However there is no intention to limit application of this invention to only the actuation cycle.

The discussion up to this point has mentioned that the substance trapped under the elements as a gas. This gas is more than likely air, although different gases may be used. Using a gas having a density less than air may increase the response time even further, as elements would have even lower pressure resistance. The damping force provided by the gas is determined by its properties, such partial pressure, density, and viscosity. The geometry of the device as well as the geometry of the gas molecules may also have and effect.

In the particular example of the interferometric modulators, these elements have a response time in the nanosecond range when operating in a vacuum. When packaged with air, they respond in the microsecond range. Therefore, it would seem that elements having a faster response time in a vacuum might employ a different gas than air to tune their response times to the optimal operating range for that type of element.

Thus, although there has been described to this point a particular embodiment for a method and apparatus for altering the response time of MEMS elements, it is not intended that such specific references be considered as limitations upon the scope of this invention except in-so-far as set forth in the following claims.

WHAT IS CLAIMED IS:

1. An array of movable elements on a substrate, each element comprising:

a cavity; and

a movable member to move through the cavity;

wherein a pressure resistance of the elements varies.

2. The array of claim 1, the movable member further comprising holes in the member to allow gas to escape when the element moves.

3. The array of claim 2, wherein different elements in the array have different patterns of holes.

4. The array of claim 1, the movable member further comprising a flexible portion and a rigid portion such that when the movable member moves through the cavity, the flexible portion collapses to trap gas between the rigid portion and the substrate.

5. The array of claim 1, the movable member further comprising a movable mirror formed from a support layer.

6. The array of claim 1, the movable member further comprising a movable mirror suspended over the cavity by at least one support post.

7. The array of claim 6, the support post further comprising support rails.

8. The array of claim 7, the support rails having holes to allow gas to escape.

9. The array of claim 1, the support layer to block edges of the movable mirror thereby trapping gas between the mirror and the substrate.

10. The array of claim 1, the pressure resistance being varied by a mechanical stiffness of the movable member.

11. The array of claim 1, the array further comprising an x-y grid of modulator elements forming a pixel, wherein modulator elements at outer edges of the pixel are arranged so as to actuate first, increasing the pressure resistance of elements at the middle of the pixel.

12. The array of claim 11, wherein the elements at the outer edge of the pixel have lower mechanical stiffness, thereby causing gas to trap under the elements at the middle of the pixel.

13. The array of claim 1, wherein the array further comprises an array of one of the group comprised of: display elements, switches, tunable capacitors, and interferometric modulator elements.

14. The array of claim 1, the array further comprising structures across the cavity from the movable element to facilitate gas flow.

15. The array of claim 1, the movable element having structures formed on it to facilitate gas flow.

16. A method of manufacturing an array of movable elements, the method comprising:

forming movable members displaced from a substrate over a cavity such that a pressure resistance of at least one of the movable members varies from a pressure resistance of others of the movable members.

17. The method of claim 16, wherein forming movable members further comprises forming movable members with holes patterned in a surface of the member.

18. The method of claim 17, wherein the holes form a first pattern on at least one of the movable members, and the holes form a second pattern on others of the movable members.

19. The method of claim 16, wherein the pressure resistance is varied by manufacturing some of the movable members to have a lower mechanical resistance, thereby causing them to actuate in such a manner as to force gas into the cavities of other movable members.

20. A method of operating an array of light modulator elements on a substrate arranged into subarrays as pixels, the method comprising:

providing an actuation signal at a first level, thereby causing a first set of elements in the pixel to actuate thereby trapping gas between other elements in the pixel and the substrate; and

providing an actuation signal at a second level, causing a second set of elements in the pixel to actuate according to a response time determined by the pressure resistance.

21. The method of claim 20, causing a first set of elements to actuate further comprises causing elements on a first edge of the pixel to actuate.

22. The method of claim 20, causing a first set of elements to actuate further comprises causing elements along a second edge to actuate simultaneously with the elements along a first edge.

23. The method of claim 20, causing a first set of elements to actuate further comprises causing elements along a second edge to actuate after the elements along the first edge.

24. The method of claim 20, causing a second set of elements to actuate according to their response time further comprises causing a second set of elements to actuate having holes patterned in their surfaces, the holes to alter the pressure resistance of the elements.

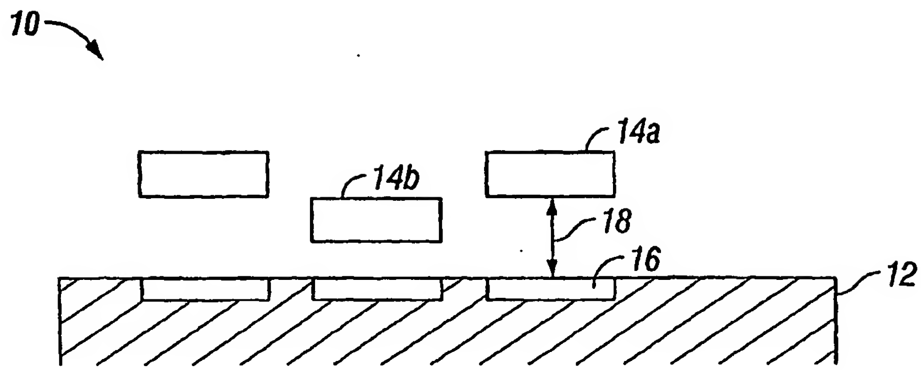

10
14a
14b
18
16
12

FIG. 1

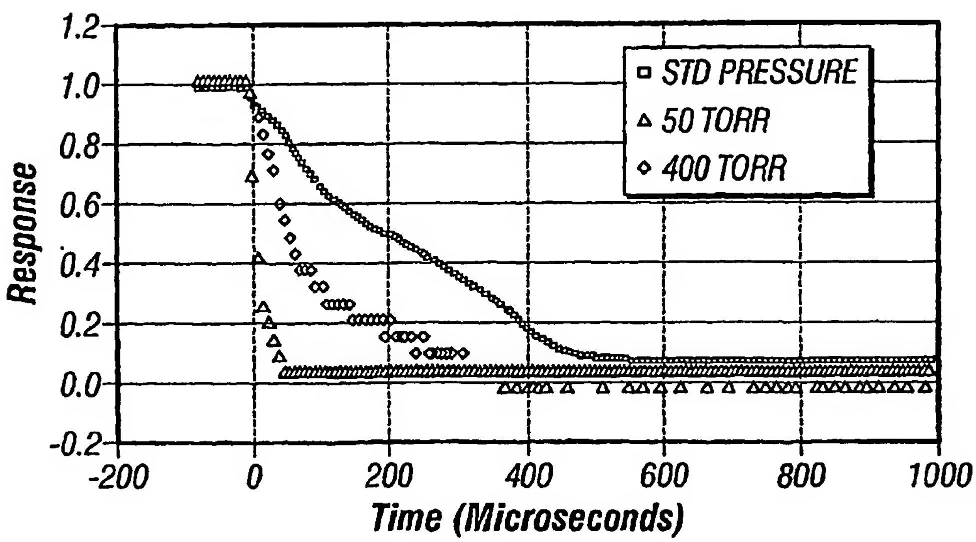
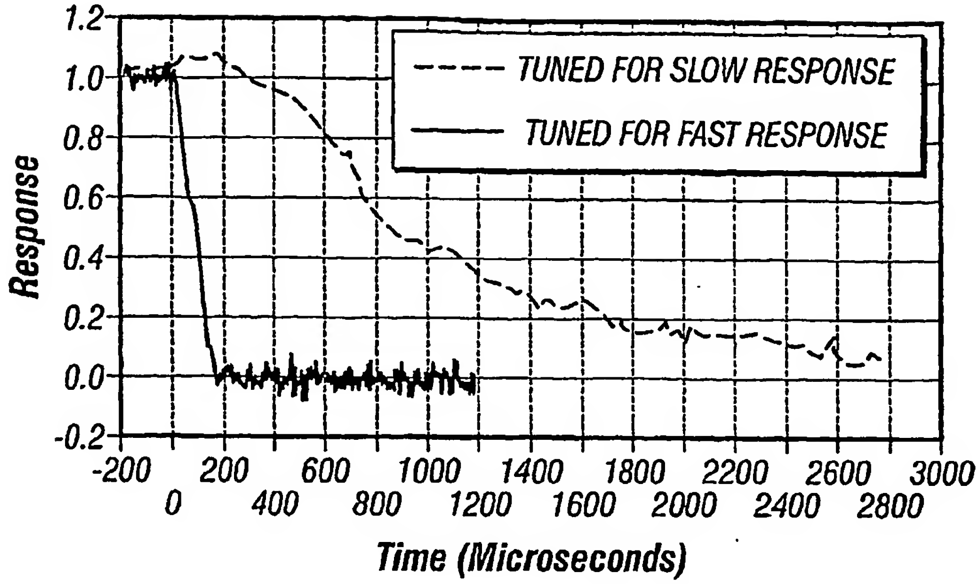
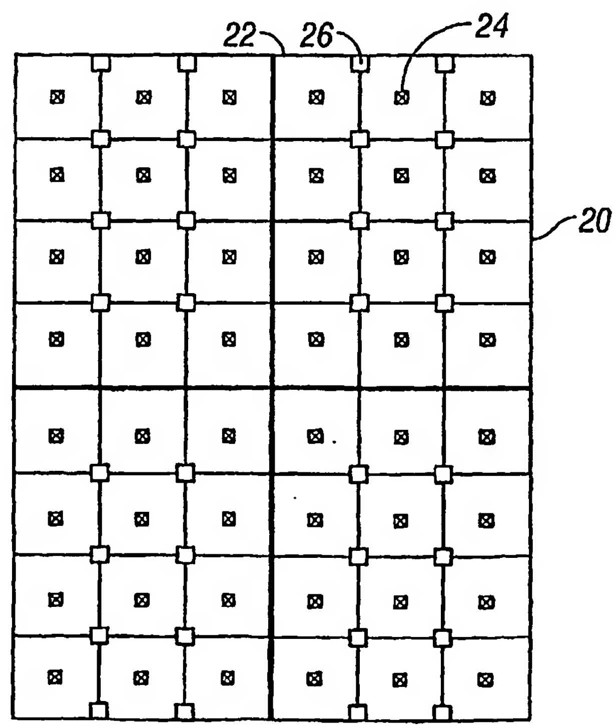

STD PRESSURE
50 TORR
400 TORR
Response
Time (Microseconds)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-200
0
200
400
600
800
1000

FIG. 2A



1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Response
TUNED FOR SLOW RESPONSE
TUNED FOR FAST RESPONSE
-200
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Time (Microseconds)

FIG. 2B



22
26
24
20

FIG. 3

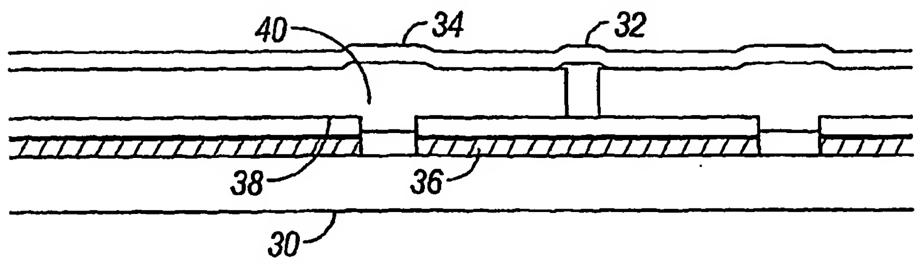


FIG. 4A

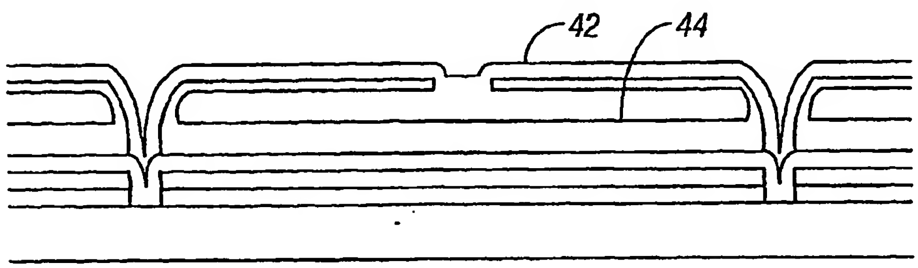


FIG. 4B

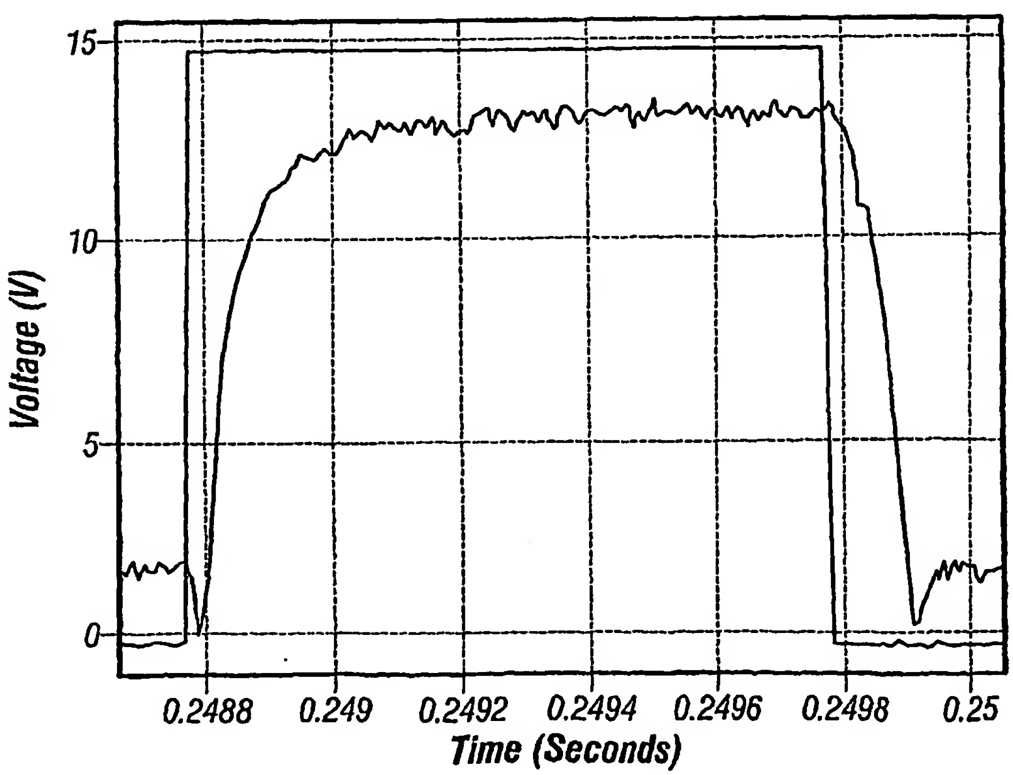


FIG. 5

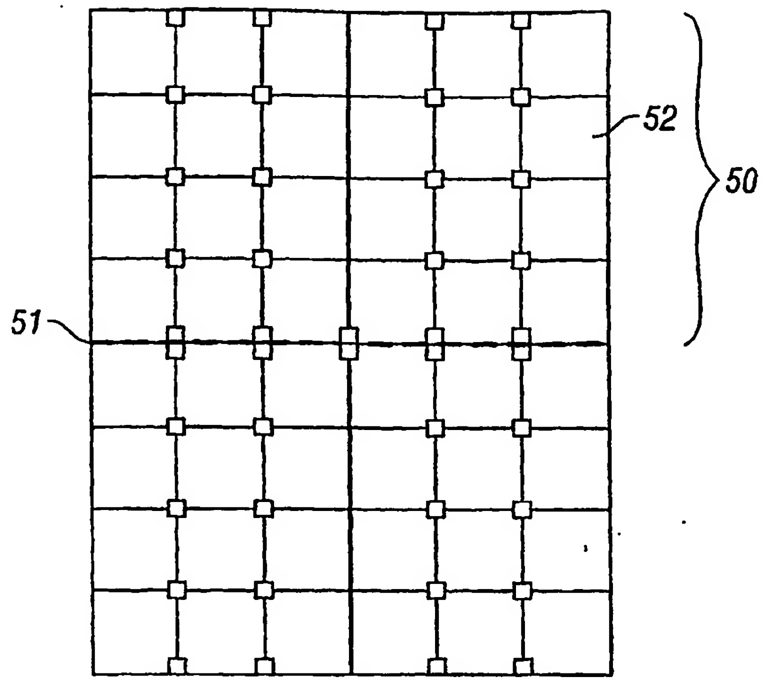
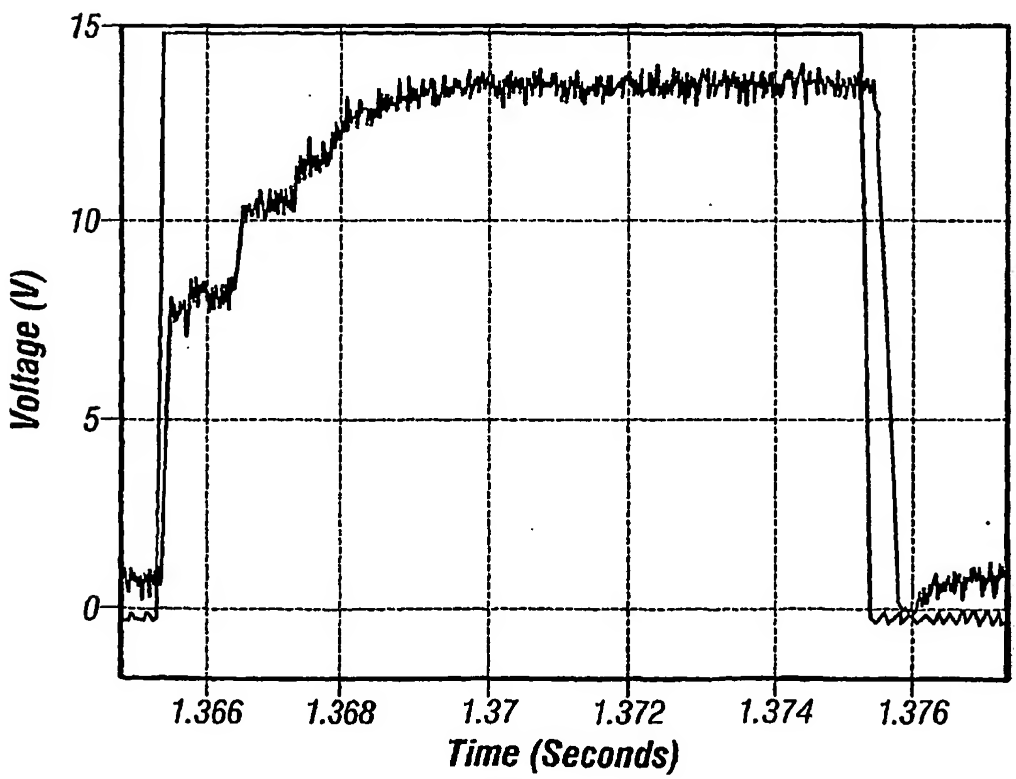

52
50
51

FIG. 6


15
10
5
0
Voltage (V)
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1.368
1.37
1.372
1.374
1.376
Time (Seconds)

FIG. 7

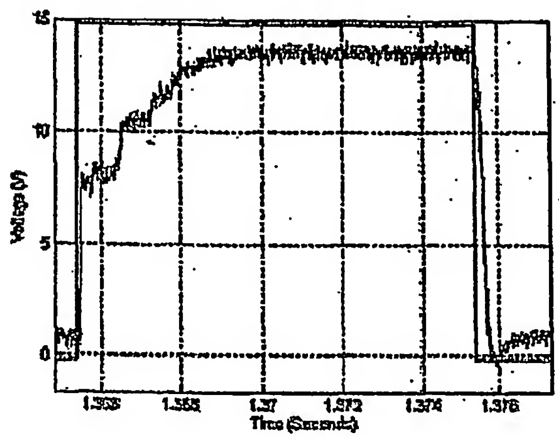

Figure 7

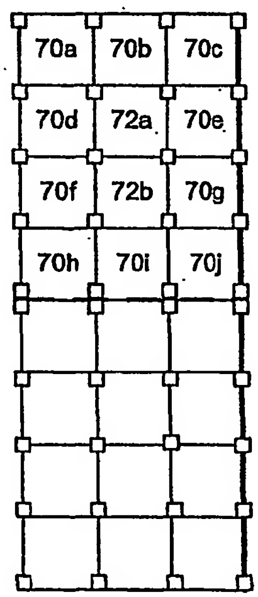

Figure 8

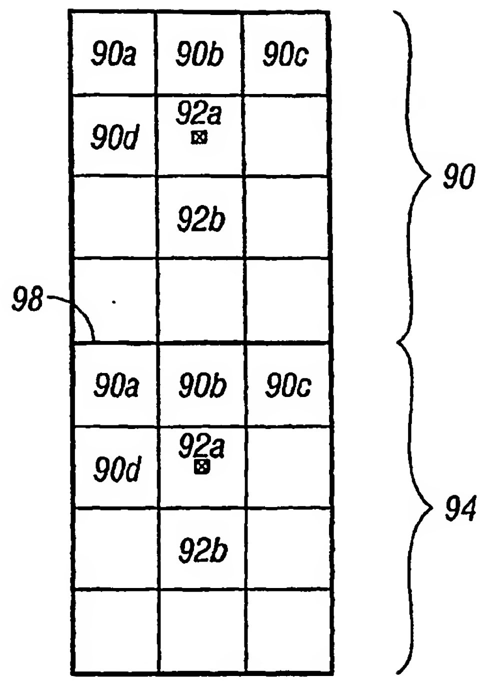

FIG. 10